DIGITAL CLIMATE INDICATORS FOR RESILIENT DESIGN: EXAMINING COMPLETENESS ACROSS CARBON AND CLIMATE RISK ANALYTICS

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Abstract

Digitalisation expanded access to design, operational and environmental data, yet whole carbon-life assessment and climate risk prediction still evolve in separate, non-interoperable workflows. This fragmentation limits climate-responsive design, especially for urban flooding and heat. The paper develops a conceptual framework for digital climate indicators that link carbon performance with predictive flood and urban heat analytics. Using a structured review of recent work on BIM-integrated life cycle assessment, digital twins, machine-learning-based hazard modelling and resilience assessment, it derives key information requirements and illustrates their application. The contribution is a set of indicator families and research directions for robust, portable climate-resilience metrics.

Introduction

Climate-responsive design in the built environment is increasingly expected to achieve two intertwined objectives: reducing greenhouse-gas emissions and maintaining acceptable performance under changing climate hazards. The IPCC AR6 Synthesis Report confirms that anthropogenic climate change is already driving widespread impacts and escalating risks for cities and infrastructures (IPCC, 2023). At the same time, buildings and infrastructure are undergoing rapid digitalisation through Building Information Modelling (BIM), Geographic Information Systems (GIS), remote sensing, Internet of Things (IoT) sensing and, more recently, digital twins (DTs) that promise continuous monitoring and predictive analytics (Zhang et al., 2025; Petri et al., 2025).

Despite this convergence, analytical workflows for mitigation and adaptation remain largely fragmented. Whole-Life Carbon (WLC) is typically assessed through life cycle assessment (LCA) and Environmental Product Declarations (EPDs), increasingly connected to BIM for automated quantity take-off (Zhang et al., 2025; Parece et al., 2025; Berges-Álvarez et al., 2024). Climate risk, by contrast, is usually analysed through hydrodynamic models, microclimate simulations, remote sensing and machine learning (ML) for hazard or susceptibility mapping (Islam et al., 2025; Ahmed et al., 2025). These workflows differ in assumptions, spatial and temporal resolution, data models and outputs, and they tend to meet, if at all, late in the process, via narrative reports rather than integrated indicators.

This separation has practical consequences. Design options optimised for WLC can inadvertently increase exposure to future flooding or overheating; conversely, adaptation measures that improve robustness may carry substantial embodied-carbon burdens that are not systematically quantified. Recent work on sustainability and resilience assessment explicitly calls for methods that link hazard, damage, recovery and environmental impacts into coherent frameworks (Sesana et al., 2024; Tanguay et al., 2024). However, there is still no shared concept of digital climate indicators that consistently connect carbon, risk and resilience analytics in digital workflows.

In this paper, a digital climate indicator is defined as a computable metric derived from integrated digital artefacts (e.g., BIM/IFC, GIS, hazard layers, scenarios) to support climate-responsive and resilient decisions.

Within the wide spectrum of climate hazards, this paper uses urban flooding and urban heat as reference, since they are high-impact in cities and supported by mature geospatial and ML ecosystems for indicator computation (Islam et al., 2025; Ahmed et al., 2025).

The aim of this paper is therefore to explore under what informational and methodological conditions indicators derived from digital artefacts, BIM/IFC models, GIS layers, sensor streams and climate-scenario data, can support climate-responsive and resilient design, with urban flooding and heat as reference hazards. The contribution is conceptual and methodological: we propose a framework for digital climate indicators, identify key information requirements, and outline research questions and directions for developing robust, interoperable metrics.

The remainder of the paper is structured as follows. Section 2 reviews recent work on BIM-integrated carbon assessment, DT-enabled dynamic LCA, ML-based flood and heat analytics, and resilience assessment methods. Section 3 introduces the indicator framework and associated information requirements. Section 4 formulates research questions and methodological directions, including a minimal operational example for flood and heat. Section 5 discusses implications and typical failure modes, and Section 6 concludes with a research agenda for digital climate indicators in the built environment.

Preliminary literature review

Digital carbon tools and BIM-integrated LCA

LCA has become the reference framework for quantifying environmental impacts of buildings and infrastructures over their life cycle and is increasingly used to support low-carbon design (Zhang et al., 2025). Recent reviews show that integrating LCA with BIM has advanced substantially in terms of automating inventory compilation. A systematic review of BIM-based LCA applications reports that BIM can automate a large fraction of life cycle inventory data extraction, reducing manual work and enabling early-stage comparisons (Parece et al., 2025). However, the same review shows that life cycle impact assessment still often requires manual mapping between BIM elements and LCA or EPD datasets, and that only a minority of studies embed results into optimisation or multi-criteria decision-support processes (Parece et al., 2025).

A complementary body of work extends the focus from environmental impacts to life cycle sustainability assessment, integrating economic and social dimensions (Berges-Álvarez et al., 2024). These studies repeatedly highlight issues of inconsistent semantics, missing metadata and limited interoperability between BIM models, classification systems and LCA datasets (Zhang et al., 2025; Berges-Álvarez et al., 2024). Even when computational pipelines are sophisticated, these informational gaps can undermine the reliability and comparability of carbon indicators. In practice, this can lead to a subtle failure mode: numerical precision without semantic robustness, where whole-life carbon values appear accurate but are conditioned on incomplete or project-specific assumptions about materials and systems. Overall, the literature suggests that digital carbon tools are moving from bespoke analyses toward more standardised workflows, but that their outputs remain sensitive to information quality and scope. For digital climate indicators, this implies that indicator design must explicitly consider semantic completeness and provenance, rather than assuming that any BIM-based LCA result is a stable quantity.

DTs and dynamic environmental indicators

DTs in the built environment are generally described as digital representations of assets or systems that are continuously updated with data from sensors, simulations and operational processes (Petri et al., 2025; Luo et al., 2024). In the last few years, DTs have been proposed as platforms for moving from static sustainability metrics to dynamic, data-driven indicators. The Building Life-cycle Digital Twin (BLDT) framework, for example, combines IoT measurements, ML models and interoperable data structures to generate time-dependent LCA outputs, enabling near real-time assessment of environmental performance and supporting predictive interventions (Petri et al., 2025). More conceptual work on DT-enabled dynamic LCA underlines the importance of embedding LCA models into broader systems of objectives, data flows and stakeholder needs, arguing that a DT can host multiple assessment lenses over time rather than producing one-off results (Luo et al., 2024).

These developments highlight an important opportunity for digital climate indicators: moving from single-snapshot values to time-series indicators that reflect changing operating conditions, retrofits and climate scenarios. At the same time, they expose new challenges. If dynamic indicators are generated without clear documentation of data provenance, model calibration, drift detection and uncertainty, DTs can become "black boxes" that amplify opacity rather than reducing it. For indicators that may be used in regulatory or financial contexts, this raises concerns about auditability and trust. Thus, any proposal for dynamic climate indicators should be accompanied by explicit information requirements and governance mechanisms.

Predictive flood analytics and risk metrics

Flood risk is a prominent climate hazard for urban areas, and data-driven approaches have proliferated alongside more traditional hydrodynamic modelling. A systematic review on urban flood susceptibility mapping synthesises remote sensing datasets, topographic and land-use variables, and ML methods, reporting that models such as random forests, gradient boosting and deep neural networks can achieve high predictive performance when sufficiently rich conditioning factors are available (Islam et al., 2025). The review also notes considerable heterogeneity in how outputs are defined (susceptibility indices, probabilities, hazard classes) and in how performance is evaluated, which complicates cross-study comparison (Islam et al., 2025).

Case studies using deep learning and hybrid schemes confirm that ML can identify dominant drivers of flood susceptibility and refine spatial resolution, but also show sensitivity to data quality, feature selection and transferability across regions (Islam et al., 2025). From the standpoint of digital climate indicators, the key point is that sophisticated hazard models do not automatically generate design-relevant risk metrics. Their outputs need to be linked to assets, functions and decision thresholds, and these links are often treated informally or in a project-specific way. Moreover, if flood susceptibility layers are not aligned with design models in terms of coordinate systems, resolution and temporal reference, there is a risk that indicators derived from them may look precise but be geometrically or temporally misaligned.

Predictive heat analytics and urban heat indicators

Urban heat and the urban heat island (UHI) effect have similarly attracted ML-based methods. A recent review of predictive approaches for UHI reports a shift from purely statistical or physics-based models towards ML, deep learning and hybrid approaches, using satellite imagery, in situ measurements and urban morphological data as inputs (Ahmed et al., 2025). Studies show that deep models can capture complex, non-linear relationships between land cover, building density, vegetation and surface temperature, yielding improved predictive accuracy compared to conventional methods (Ahmed et

Table 1: Literature-gap matrix

Literature stream	Carbon performance	Flood risk	Urban heat	Resilience	Cross-domain integration
BIM-integrated LCA	✓✓	✗	✗	✗	✗
Flood susceptibility & ML models	✗	✓✓	◐	✗	✗
Urban heat prediction models	✗	✗	✓✓	✗	✗
Resilience assessment frameworks	◐	◐	◐	✓✓	◐
Present work	✓	✓	✓	✓✓	✓✓

Legend:
✓✓ = core focus ✓ = addressed ◐ = partially addressed ✗ = not addressed

al., 2025). However, the same review emphasises limitations in generalisability, given that models trained on one urban context may perform poorly when applied elsewhere without retraining or adaptation (Ahmed et al., 2025).

For digital climate indicators, heat prediction is directly relevant to cooling loads, indoor overheating risk and outdoor comfort. Yet, as with flood models, heat predictions are typically published as thermal maps or statistics, not as indicators tied to specific buildings, spaces or design decisions. Without clear information on spatial correspondence, scenario assumptions and temporal resolution, integrating such outputs into carbon and resilience indicators becomes difficult.

Resilience assessment methods and metrics

Resilience assessment in the built environment has evolved from qualitative descriptions to more structured frameworks and tools. A critical review of resilience assessment tools for the built environment notes a proliferation of methods but also fragmentation, inconsistent definitions and limited empirical validation (Cerè et al., 2017). The authors argue that many tools remain diagnostic rather than operational, and that the relationship between resilience and sustainability is often under-specified (Cerè et al., 2017).

More recent work proposes quantitative key performance indicators (KPIs) for risk and resilience assessment of assets exposed to climatic and non-climatic hazards, combining concepts such as robustness, redundancy, exposure and recovery (Ricciardi et al., 2025). A systematic review of sustainability and resilience assessment methods in the construction sector further documents the uneven development of approaches and calls for integrated frameworks that explicitly link hazard scenarios, damage, recovery trajectories and environmental impacts (Sesana et al., 2024). In a related contribution, the sustainability of resilient built environments is examined by combining performance-based damage assessment under hazards with LCA of repair and retrofit interventions, illustrating both synergies and trade-offs between resilience and environmental performance (Tanguay et al., 2024).

Taken together, this literature indicates that resilience is conceptually rich and quantitatively expressible, but that indicators remain heterogeneous and only partially integrated into digital design and management tools. For digital climate indicators, this reinforces the need to anchor resilience metrics in clear functional definitions and information requirements.

While the reviewed literature demonstrates significant progress within individual analytical domains, it also reveals a persistent fragmentation across carbon assessment, climate risk modelling and resilience analysis. BIM-integrated life cycle assessment workflows primarily address mitigation objectives, but rarely engage with hazard exposure or recovery dynamics. Conversely, flood and urban heat modelling studies provide increasingly accurate hazard predictions, yet typically remain detached from asset-level carbon implications and resilience metrics. Resilience assessment frameworks offer conceptual and quantitative tools to describe system response and recovery but are often weakly connected to digital design and hazard analytics.

Cross-cutting gaps and integration challenges

Across the reviewed literature, a recurring limitation is the lack of integration between analytical domains that are increasingly interdependent under climate change. Carbon assessment studies typically operate at building scale and rely on static or weakly scenario-dependent assumptions, while flood and urban heat modelling often adopt district or city scales driven by climate scenarios that are not aligned with those used in mitigation analyses. This mismatch in spatial and temporal scales complicates the joint interpretation of results and limits their decision relevance.

A further cross-cutting gap concerns uncertainty communication. While uncertainty is acknowledged in both life cycle assessment and climate risk modelling, it is rarely propagated or interpreted consistently when outputs from different domains are combined. As a result, decision-makers may be exposed to indicators that appear precise but embed heterogeneous and implicit assumptions.

Finally, the mapping between hazards, asset performance and functional consequences remains weakly formalised in much of the literature. Flood and heat indicators often describe exposure or intensity, while resilience metrics attempt to capture response and recovery, yet explicit links between hazard levels, asset degradation and downtime are rarely integrated into digital workflows.

Table 2: Indicator families, information requirements, and typical gaps for flood- and heat-related applications

	Key Information elements	Alignment needs	Typical gaps
Carbon performance (WLC)	• BIM-based quantities • Material specifications • Environmental Product Declarations (EPDs) • Operational profiles • Decarbonisation scenarios	• Semantic alignment between BIM elements and LCA datasets • Temporal alignment with energy and grid scenarios	• Missing or inconsistent material metadata • Partial system boundaries • Limited transparency on scenario assumptions
Climate risk (flood & heat)	• Flood susceptibility or hazard maps • Urban heat metrics (e.g. land surface temperature, heat indices) • Exposure data • Basic vulnerability attributes	• Spatial alignment between hazard layers and asset geometries • Consistent resolution and coordinate systems • Scenario coherence	• Resolution mismatch • Limited transferabilit y of ML models • Weak linkage between hazard scores and asset-level consequences
Resilience performance	• Functional definitions • Performance thresholds • Recovery time assumptions • Interdependency between systems	• Temporal alignment between hazard events and recovery models • Explicit performance metrics	• Qualitative or poorly validated recovery assumptions • Lack of standardised resilience metrics

These gaps motivate the need for a structured framework that explicitly connects carbon performance, climate risk and resilience through shared information requirements and transparent alignment processes

Table 2 synthesises these patterns by positioning the main literature streams against the three indicator families considered in this paper, highlighting both areas of maturity and structural gaps, and it motivates the need for an integrative indicator framework capable of bridging these domains.

Proposed framework

Concept of digital climate indicators

The aim of the present work consists in defining a digital climate indicator as a metric derived from digital representations of the built environment (e.g.. BIM and IFC models, GIS layers, sensor data and climate-scenario datasets) to support climate-responsive and resilient decision-making. Unlike generic performance metrics, digital climate indicators are explicitly conditioned on the quality, completeness and alignment of the underlying information from which they are computed.

The need for such indicators emerges from the growing availability of digital data and analytical tools, coupled with the persistent separation between mitigation-oriented assessments (e.g. whole-life carbon, WLC) and adaptation-oriented analyses (e.g. climate risk mapping). Recent literature shows that while BIM-integrated life cycle assessment (LCA) workflows and DTs enable increasingly automated and dynamic carbon assessment (Parece et al., 2025; Petri et al., 2025), climate risk analytics, particularly for flooding and heat, are often developed independently using geospatial data and machine learning (ML) models (Islam et al., 2025; Ahmed et al., 2025). As a result, outputs are difficult to combine in a coherent and decision-relevant manner. Digital climate indicators are therefore not conceived as new standalone metrics, but as integrative constructs that explicitly link carbon performance, climate risk and resilience performance under clearly defined information requirements. Their value lies not only in numerical results, but in their ability to make assumptions, dependencies and uncertainties explicit across heterogeneous digital workflows.

Indicator families and hazard focus

The development of the indicator is structured along three indicator families: carbon performance, climate risk, and resilience performance. These families correspond to distinct but interdependent decision questions: how much an asset contributes to climate change, how exposed it is to climate hazards, and how it performs and recovers when those hazards occur. Within the broad spectrum of climate-related hazards, this framework focuses explicitly on urban flooding and urban heat. This choice is motivated by three considerations. First, flooding and heat are consistently identified as dominant climate threats for urban areas, with significant impacts on infrastructure functionality, public health and economic activity (IPCC, 2023). Second, both hazards are supported by relatively mature digital ecosystems, including remote sensing, urban morphology datasets and ML-based susceptibility or prediction models, making them suitable for indicator computation at building and district scales (Islam et al., 2025; Ahmed et al., 2025). Third, flood and heat hazards exhibit strong interactions with both operational and embodied carbon, as well as with resilience metrics such as downtime and recovery, making them particularly relevant for illustrating cross-domain trade-offs. By concentrating on flooding and heat, the framework achieves methodological clarity while remaining representative of broader multi-hazard challenges faced by climate-resilient design.

Information requirements and alignment conditions

A recurring finding across the reviewed literature is that the main barriers to integrated climate assessment are not purely computational, but informational. The computation of digital climate indicators depends on the availability, alignment and interpretability of heterogeneous data sources. Table 2 synthesises the key information requirements associated with each indicator family, with explicit reference to flood and heat-related applications. For carbon performance indicators, such as WLC, required information includes BIM-based quantities, material specifications, Environmental Product Declarations (EPDs), operational profiles and decarbonisation scenarios (Zhang et al., 2025; Berges-Álvarez et al., 2024). Semantic alignment between BIM elements and LCA datasets is critical, missing or inconsistent metadata can lead to systematic underestimation or exclusion of relevant components. For climate risk indicators, flood susceptibility maps and urban heat metrics must be spatially linked to asset geometries through consistent coordinate systems and resolution. ML-based models can provide high-resolution hazard predictions, but their outputs must be interpreted within explicit scenario and validation boundaries to avoid false precision (Islam et al., 2025; Ahmed et al., 2025).

For resilience performance indicators, information requirements extend beyond hazards to include functional definitions, performance thresholds and recovery assumptions. Literature on resilience assessment highlights that these aspects are often weakly formalised or treated qualitatively, limiting indicator comparability and robustness (Cerè et al., 2017; Sesana et al., 2024).

Across all families, spatial alignment, temporal and scenario transparency, and uncertainty representation emerge as cross-cutting requirements. Table 2 identifies the minimum information elements required for each indicator family. Figure 1 translates these requirements into an operational alignment sequence and it conceptually illustrates the proposed workflow for computing digital climate indicators by explicitly articulating how heterogeneous digital data sources are transformed into decision-relevant metrics. The workflow is structured around three main stages: data sourcing, alignment and processing, and indicator computation. Rather than assuming seamless interoperability, the figure makes visible the intermediate alignment steps (i.e.; semantic enrichment, spatial matching between assets and hazard layers, temporal and scenario harmonisation, and uncertainty characterisation) that condition the correctness and robustness of the resulting indicators. By positioning these steps explicitly between data ingestion and indicator outputs, the workflow highlights where information gaps, misalignments or implicit assumptions may propagate into carbon, flood and heat risk, and resilience metrics. This articulation provides the basis for a critical discussion of typical failure modes and limitations, which are addressed in the following section.

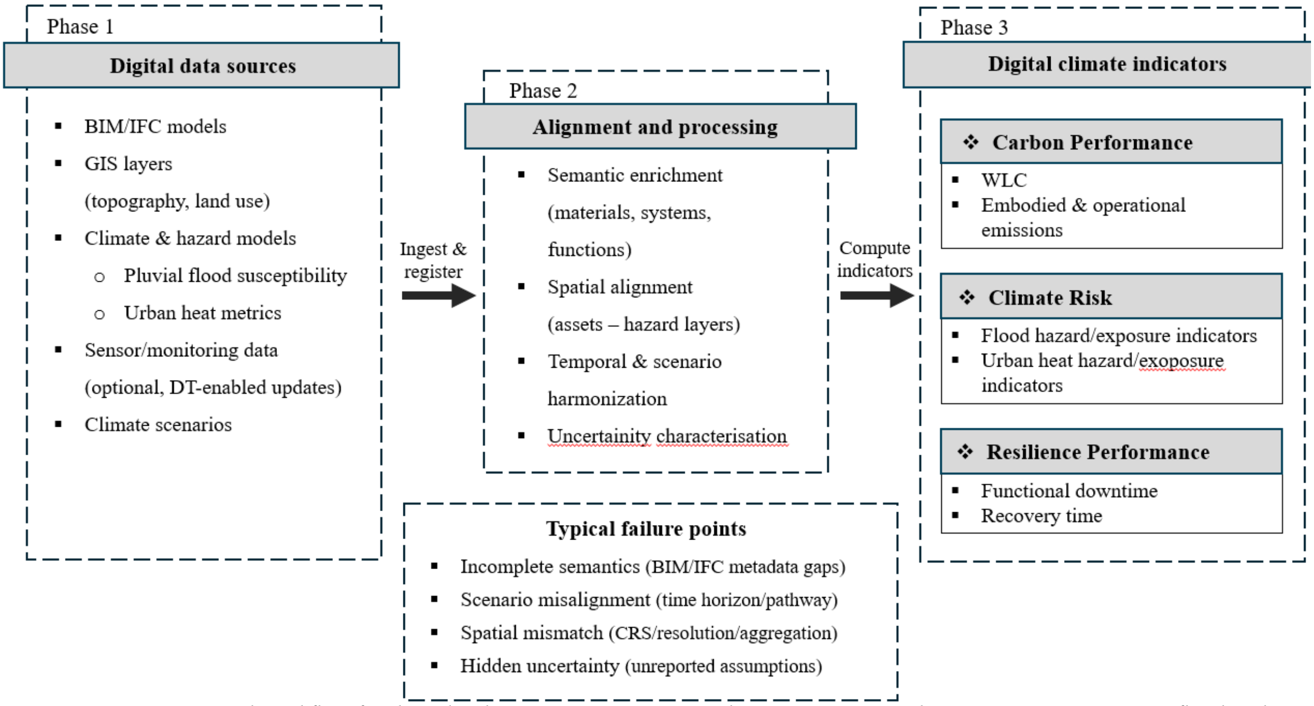

Figure 1: Conceptual workflow for digital indicators' computation in three action-oriented stages, integrating WLC, flood and urban heat risk, and resilience performance

Indicator validity, scale, and decision context

A critical aspect of digital climate indicators concerns their validity across scales and decision contexts. Indicators computed at building scale may be suitable for early design choices or retrofit comparisons, whereas district-scale indicators are more relevant for planning decisions, infrastructure prioritisation and portfolio-level assessment. The proposed framework does not prescribe a single scale of application; instead, it requires that the scale of indicator computation is explicitly aligned with the intended decision context.

In this perspective, indicator validity is not primarily defined by predictive accuracy, but by internal consistency, transparency of assumptions and sensitivity to information completeness. Whole-life carbon indicators, for example, may support robust comparison between alternative design strategies even when absolute emission values are uncertain, provided that system boundaries, material mappings and scenarios are consistently defined.

Similarly, flood and urban heat indicators are often more informative when used to position options relative to one another rather than to predict exact hazard impacts. By making scale and decision context explicit, the framework helps prevent the misuse of indicators outside their domain of validity and supports more appropriate interpretation of results. This shift from optimisation to comparative reasoning is particularly relevant for climate-responsive design, where decisions must be made under deep uncertainty and evolving boundary conditions.

Research questions and methodological directions

The proposed framework motivates a set of research questions aimed at advancing the development and use of digital climate indicators for flood- and heat-related applications. Such questions are derived from the literature review and framework synthesis and are presented as a research agenda rather than being fully answered within the present contribution.

RQ1 - Indicator correctness

Under what information conditions can integrated carbon, flood/heat risk and resilience indicators be considered correct representations of climate performance? This question concerns the relationship between indicator definitions and the completeness and consistency of the underlying digital information.

RQ2 - Portability and interoperability

To what extent can indicators computed for flood and heat hazards be reproduced across projects, tools and local contexts? Given the documented variability in BIM semantics, LCA datasets and ML-based hazard models, this question addresses the limits of indicator transferability (Parece et al., 2025; Islam et al., 2025).

RQ3 - Uncertainty and robustness

How should uncertainty from climate scenarios, hazard models and recovery assumptions be propagated and communicated through digital climate indicators? Prior work on sustainability and resilience assessment suggests that robustness-oriented representations may be more decision-relevant than single deterministic values (Sesana et al., 2024; Tanguay et al., 2024).

RQ4 - Dynamic updating through DTs

When indicators are computed and updated within DT-based environments, how can provenance, versioning and validation be managed to avoid drift and loss of comparability over time (Petri et al., 2025; Luo et al., 2024)?

Mini operational example: flood- and heat-responsive indicators

Aiming at illustrating the applicability without introducing a full case study, a minimal operational example is presented below, applying the workflow introduced in Figure 1 to the case of urban flooding and urban heat, illustrating how the same sequence of data ingestion, alignment and indicator computation can be instantiated for concrete climate hazards. The example is intentionally procedural (computability-focused) and does not claim empirical validation of indicator values.

In this example, the digital artefacts required at each step correspond directly to the information requirements outlined in Table 2. Concretely, the BIM/IFC inputs must be enriched with the minimum attributes required for WLC mapping (e.g., construction assemblies, key system descriptors, and stable identifiers to link to EPD datasets), as well as basic functional zoning information to support resilience metrics. The flood and heat layers must then be aligned to asset geometries through explicit georeferencing and scale handling (e.g., aggregation rules when raster resolution is coarser than building/zone geometry, and consistent assumptions on reference elevation for flood susceptibility interpretation). Finally, temporal and scenario harmonisation is required to avoid false precision, ensuring that carbon and hazard indicators refer to compatible horizons and scenario choices (e.g., heat-related operational impacts under specified climate pathways).

Carbon performance indicators are derived from a BIM-based WLC assessment, including embodied emissions associated with building fabric and adaptation measures, as well as operational emissions influenced by increased cooling demand under projected heat conditions. These computations assume the availability of semantically enriched BIM models and scenario-based energy profiles, but do not require real-time monitoring or full operational calibration.

Climate risk indicators are computed by spatially linking asset geometries to pluvial flood susceptibility maps and urban heat metrics derived from remote sensing and machine-learning-based models. At this stage, the workflow relies on consistent spatial resolution and explicit scenario selection rather than on hazard model optimisation.

Resilience performance is expressed through simplified metrics such as functional downtime and recovery time following representative flood and heat events. These metrics are not intended as predictive estimates, but as comparative indicators that allow alternative design or adaptation options to be positioned relative to one another.

By following the workflow in Figure 1, the example demonstrates how carbon, flood and heat risk, and resilience indicators can be jointly computed under clearly stated assumptions. The resulting indicators support comparative reasoning across options, rather than optimisation, and make explicit where trade-offs and uncertainties enter the decision process.

Discussion

The proposed framework aims to respond to recurrent limitations observed in current digital climate assessment practices through the research questions introduced previously. Rather than providing definitive solutions, the framework clarifies how integrated digital climate indicators can be constructed and interpreted under explicit conditions, and where their limitations remain.

Indicator correctness (RQ1) emerges primarily as an information-driven challenge. As illustrated by the workflow in Figure 1, the framework makes explicit that indicator validity depends on semantic completeness, spatial alignment and scenario consistency across heterogeneous digital inputs. This represents a clear advance over approaches in which carbon, flood or heat indicators are computed independently, often masking underlying assumptions. At the same time, the framework does not eliminate epistemic uncertainty: if information is incomplete or misaligned, indicators may still be internally consistent yet only partially representative. The contribution therefore lies in making such limitations visible rather than implicit.

Portability and interoperability (RQ2) are addressed by structuring indicators around shared information requirements rather than tool-specific implementations. Table 2 highlights how carbon, climate risk and resilience indicators rely on different datasets and modelling choices, many of which are context dependent. While this limits full transferability, the framework supports partial portability by enabling indicators to be recomputed consistently across projects, if information requirements are met. A remaining challenge concerns machine-learning-based flood and heat models, whose sensitivity to local training data constrains cross-context comparability and requires careful documentation.

Uncertainty and robustness (RQ3) are treated implicitly through the framework's emphasis on comparative rather than absolute indicator interpretation. As suggested by the operational example, integrated indicators are more effective in positioning design or adaptation options relative to one another than in providing precise predictive values. This shift aligns with recent work advocating robustness-oriented assessment in climate-resilient design but also raises challenges in communicating uncertainty without undermining decision confidence. The framework offers a structure for this communication, but methodological advances are still needed to operationalise uncertainty propagation across indicator families.

Dynamic updating through digital twins (RQ4) represents both an opportunity and a risk. DT-based environments enable indicators to be recalculated as new data become available, supporting adaptive decision-making over time. However, without explicit governance mechanisms, such as versioning, provenance tracking and validation rules, dynamic updating may compromise indicator comparability and trust. The framework highlights these risks by positioning updating as a conditional capability rather than an inherent benefit, underscoring the need for controlled integration rather than continuous recalculation.

The framework does not aim to provide empirical validation of indicator values, nor to define new standards, thresholds or regulatory metrics. Its purpose is to clarify the informational and alignment conditions under which integrated digital climate indicators can be computed and meaningfully interpreted.

Despite its potential, the framework has deliberate limitations: it does not harmonise underlying carbon, flood/heat, or resilience models, and comparability remains dependent on the transparency and context-dependence of adopted datasets and assumptions. Addressing these limitations requires empirical multi-context testing and governance mechanisms (e.g., provenance, versioning and validation rules), which are beyond the scope of this contribution.

Overall, the proposed framework enables a more transparent and structured engagement with carbon, flood and heat risk, and resilience indicators, while also exposing the practical and methodological challenges that remain. Its value lies less in resolving these challenges than in providing a coherent basis for addressing them in future empirical and methodological work.

Conclusion

This paper has addressed the challenge of linking mitigation and adaptation-oriented analyses in the built environment by proposing a framework for digital climate indicators that integrate whole-life carbon performance, flood and urban heat risk, and resilience metrics. While digitalisation has enabled unprecedented access to data and analytical tools, current workflows remain fragmented, limiting their ability to support climate-responsive and resilient design decisions.

Building on a structured review of recent literature, it is shown that the technical components required for integration, BIM-based carbon assessment, DT-enabled dynamic analysis, ML-based hazard modelling and resilience metrics, are already available, but rarely combined under explicit information requirements. By organising indicators into three families and articulating the alignment steps needed to compute them, the proposed framework clarifies where and why integration succeeds or fails. The workflow illustrated in Figure 1 and the information mapping in Table 2 provide a conceptual scaffold for moving from isolated analyses to coherent, decision-relevant indicators. The focus on urban flooding and urban heat has allowed the framework to be grounded in high-impact, data-rich hazards that are representative of broader climate challenges. The mini operational example demonstrates how integrated indicators can reveal cross-domain interactions and trade-offs that would remain hidden in siloed assessments, even without a full case study.

The lasting contribution of this work lies not in defining new metrics, but in reframing indicator development as an information-driven and methodologically explicit process. Taken together, the framework allows a first set of methodological answers to the proposed research questions to be stated. Regarding indicator correctness (RQ1), the paper clarifies that "correctness" is conditional on explicit information requirements and alignment steps: integrated indicators become fragile when BIM/IFC semantics are incomplete for WLC mapping, when hazard layers are not spatially matched to assets, or when temporal/scenario assumptions are inconsistent. Regarding portability (RQ2), the framework supports recomputation across projects by making the required inputs and mappings explicit, but comparability remains constrained by context-dependence of datasets and by the transferability limits of flood and heat models. Regarding uncertainty (RQ3), the paper supports a robustness-oriented interpretation: the most defensible use of integrated indicators at early stages is comparative reasoning across options under stated scenarios, rather than absolute prediction. Finally, for dynamic updating (RQ4), the framework highlights that DT-enabled recalculation is useful only under governance mechanisms (provenance, versioning and validation rules) that preserve traceability and comparability over time. In this perspective, digital climate indicators should be treated as information-driven constructs whose validity depends on explicit assumptions, alignment conditions and decision context. By reframing indicator development around information requirements and integration workflows, this paper contributes a structured basis for linking carbon performance, flood and urban heat risk, and resilience within digital design and assessment processes. Future work will focus on applying the proposed framework to real urban case studies exposed to flood and heat stress, to test indicator computability, sensitivity to information completeness, and usefulness for comparing design and adaptation options. Such applications will be essential to further consolidate the framework and to support the responsible use of integrated indicators in climate-responsive and resilient design.

From a practical standpoint, these conclusions suggest that deployment-oriented work should treat information requirements and alignment procedures as first-class deliverables, alongside algorithmic components. For research evaluation, this implies reporting integration effort (e.g., BIM/IFC enrichment steps, spatial matching rules, scenario harmonisation choices, and governance overhead) as part of methodological transparency, rather than focusing solely on model accuracy.

Ultimately, advancing digital climate indicators requires not only better models, but clearer assumptions, shared information requirements and critical reflection on how indicators are used in practice.

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